

EFFICIENT CONVERSION OF ENERGY IN THE CONDITIONS OF TRIGENERATION OF HEAT, COOLING AND ELECTRIC POWER

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Abstract. The paper presents the efficiency comparison of the trigeneration system with respect to the separate generation of heat, cooling and electricity. Trigeration Primary Energy Saving (TPES) indicator was adopted as an assessment criterion. The results of calculations are presented, based on which the analysis of the effect of a variable rate of heat used for cooling, as well as the turbine inlet temperature, on trigeneration system operations have been performed.

Key words: trigeneration, CCHP, energy efficiency, primary energy saving

EFEKTYWNA KONWERSJA ENERGII W TRÓJGENERACJI CIEPŁA, CHŁODU I ENERGII ELEKTRYCZNEJ

Streszczenie. W pracy przedstawiono porównanie wydajności układu trójkeneracyjnego w odniesieniu do układu z oddzielną generacją ciepła, chłodu i energii elektrycznej. Jako kryterium oceny przyjęto wskaźnik względnej oszczędności energii pierwotnej (ang. Trigeration Primary Energy Saving) TPES. Zaprezentowano wyniki obliczeń symulacyjnych, na podstawie których przeprowadzono analizę wpływu zmiennych wartości udziału ciepła wykorzystywanego do produkcji chłodu oraz temperatury spalin na wlocie do turbiny na efektywność pracy układu trójkeneracyjnego.

Słowa kluczowe: trójkeneracja, CCHP, efektywność energetyczna, oszczędność energii pierwotnej

Introduction

The process of electricity generation in conventional power plants is characterised by a relatively low efficiency, which for power plants using coal and oil as their fuel is approximately 33%. This is due to the fact that only a small part of the primary thermal energy can be used to produce mechanical energy and further electrical energy.

Utilisation of wasted thermal energy is a solution which significantly improves the energy efficiency of the process of energy generation. Among the systems that use waste heat particular interest is in the possibility of using this energy to warm up the heat carrier in heating systems. Such solutions are defined as cogeneration systems and are used especially in municipal thermal power plants [6, 8]. Depending on the applied technology the obtained energy efficiency may exceed even 70%.

Further increase of energy efficiency can be achieved by introducing additional processing systems, which utilise the primary thermal energy to a greater extent. Taming this heat for the production of cooling can increase the total efficiency of over 80%. Solutions of this type, producing useful energy in its various forms, are defined as polygeneration systems and systems of combined generation of electricity and thermal energy in the form of heat and cold as trigeneration systems.

Demonstration of the benefits of this type of technology is the main idea of this article. The scope of this research includes analysis of trigeneration processes, and the presentation of the criteria of assessment of primary energy use for cooling production. In the next sections, these criteria are the basis for the calculation and analysis of the energy efficiency of trigeneration systems. In the final part of the paper the results of studies are summarised, conclusions are formulated and typical users of this type of generation systems are proposed.

1. The idea of trigeneration

Trigeneration is the simultaneous or consecutive production of three products of different energy grades from a single primary energy source. In this article, attention is drawn to trigeneration as a process which is important from the point of view of primary energy savings.

Trigeneration or combined cooling, heat and power (CCHP) is based in a classical case upon CHP systems (Fig. 1), which produce electricity and heat, coupled to absorption chillers, which produce cold, fired with heat and a small amount of electricity generated in cogeneration.

The main objective of trigeneration is to use seasonal excess heat and wasted energy (energy is contained in the exhaust gases and hot water from the engine cooling system). Up to 80% of this wasted heat can be converted into chilled water, which increases the overall efficiency of power plants.

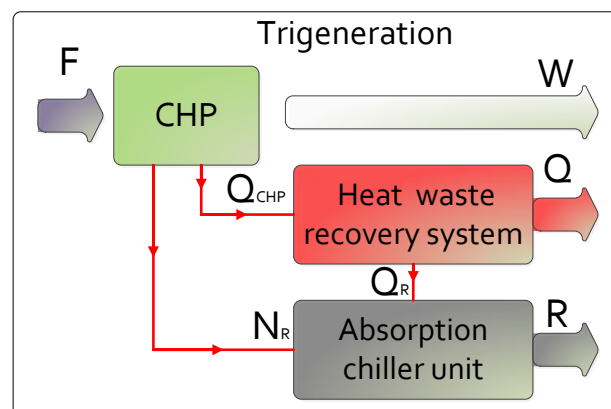


Fig. 1. Diagram of the principle of trigeneration

The performance of trigeneration is considerably higher in comparison to separate production, but lower than cogeneration [7], and can become more profitable when the recovered heat to generate cold will be used outside the heating season for the purpose of air conditioning. For this reason, it is important to determine the demand for all types of energy at the same time.

2. Assessment criterion of system conversion

Traditional energy efficiency indicators used to assess the performance of the combined production of electricity and heat do not consider all the operating conditions of the CCHP units, all interactions between equipment and all energy flows inside the whole energy system. Therefore, it is essential to determine the indicators describing the trigeneration system.

The most commonly used indicators for the analysis of the trigeneration system are:

- Energy Utilisation Factor Euf.
- Coefficient of Performance Cop.
- Trigeration Primary Energy Saving Tres.
- Power to Heat Ratio Phr.

The Energy Utilisation Factor for the trigeneration system is the simplest criterion of assessment of the system's effectiveness. The *EUF* indicator is based on the first law of thermodynamics and represents the overall energy efficiency of the system, gives a quick indication of the amount of thermal energy contained in the fuel actually converted to usable energy [4]:

$$EUF = \frac{W + Q + R}{F} \quad (1)$$

where W is the electrical power output, Q is the useful thermal energy output, R is the refrigerating output, F is the total fuel input (primary energy).

Coefficient of performance is generally defined as the ratio of energy obtained (output) to the energy consumed by the cooling device (input). Moreover, the *COP* indicator depends on the specified device and can be determined in different ways. The performance coefficient of the trigeneration system with simultaneous production of heat and cold is [9]:

$$COP = \frac{R}{Q_R + N_R} \quad (2)$$

where R is the refrigerating output, N_R is the total electrical energy consumed by the hot-water pump, the cooling-water pump and the chilled-water pump, and Q_R is the heat input to the generator.

Trigeneration Primary Energy Saving (*TPES*) is the most applied indicator of assessment of reduction in primary energy consumption, which can be achieved by using the trigeneration system instead of separate production of heat (i.e. fuel fired boilers), cold (i.e. compression chillers) and electricity (i.e. centralized power systems) [1]:

$$TPES = \frac{F^{sp} - F_{CCHP}}{F^{sp}} \quad (3)$$

where F^{sp} is the primary energy consumption by the conventional separate generation systems to satisfy the same demand of different energy types generated from the CCHP system, and F_{CCHP} is the fuel thermal energy input (primary energy) into the whole CCHP system.

Analysis of the two power systems, trigeneration and separate generation, was performed taking into consideration only the actual input and output energy flow. The amounts of energy supplied to the systems in the form of primary fuel F and energy flowing out from the systems in the form of electrical energy W and thermal energy (heat Q and cooling R) have been defined.

The primary energy consumption in separate production is the sum of the fuel consumption of individual systems producing electricity, heat and cooling [10], thus:

$$F^{sp} = \frac{W}{\eta_W^{sp}} + \frac{R}{COP^{sp} \cdot \eta_W^{sp}} + \frac{Q}{\eta_Q^{sp}} \quad (4)$$

where η_W^{sp} and η_Q^{sp} are the reference efficiencies for the conventional separate generation of electricity and thermal energy respectively, and COP^{sp} is the coefficient of performance of the compression chiller.

The fuel consumption in trigeneration is:

$$F_{CCHP} = \left(\frac{R}{COP} + Q \right) \frac{1}{\eta_Q} = \frac{W}{\eta_W} \quad (5)$$

where η_W is the trigeneration electrical efficiency, and η_Q is the trigeneration thermal efficiency.

The result of equations (4), (5) and (3) is:

$$TPES = 1 - \frac{F_{CCHP}}{\frac{W}{\eta_W^{sp}} + \frac{Q}{\eta_Q^{sp}} + \frac{R}{COP^{sp} \eta_W^{sp}}} \quad (6)$$

Trigeneration is considered to be high performance if the calculated values of the Trigeneration Primary Energy Saving indicator satisfy the condition: $TPES \geq 0$.

The selection of appropriate parameters of the electric and heat load has influence on the fuel efficiency. Power to Heat Ratio indicates the proportion of electricity to the useful heat energy produced in CHP [12]:

$$PHR = \frac{W}{Q_{CHP}} = \frac{\eta_W}{\eta_Q} \quad (7)$$

Indicators defined in section (1-7) constitute the basis for the analysis and formulation of the evaluation of energy conversion in a trigeneration system. The issue is being developed in the next section of the article.

3. Calculations of the conversion factors and analysis of the obtained results

Trigeneration systems use different types of engines which can operate on a variety of fossil fuels (such as natural gas, fuel oil, etc.) as well as renewable energy sources (such as biomass, landfill gas, geothermal energy, etc.). Typical trigeneration systems are built on the basis of internal combustion reciprocating engines or gas-turbines and absorption chiller driven by exhaust gases, steam or hot water. A gas-turbine power plant operating on the ideal Brayton cycle is considered in this paper (Fig. 2). It is equipped with a heat recovery exchanger powered by exhaust gas leaving the turbine. The recovered heat is used further for heating and cooling.

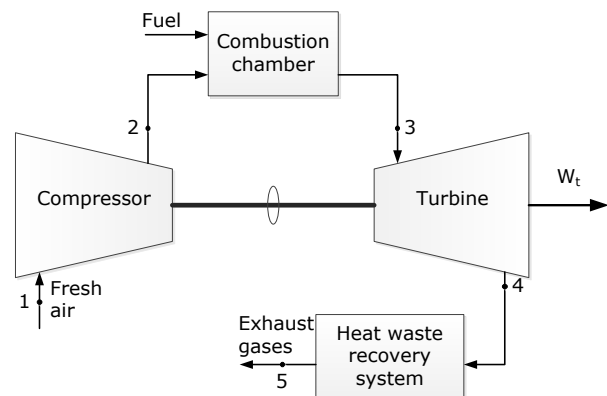


Fig. 2. The schematic diagram of a gas-turbine engine

Figure 3 shows the P-V and T-S property diagrams for phase-change processes of a gas-turbine engine. The ambient air is drawn into the compressor (point 1), where it is isentropic pressurised and its temperature and pressure are raised (point 2). The compressed air then runs through a combustion chamber, where the fuel is burned in a constant-pressure process. The resulting high-temperature gases then enter the turbine (point 3), where they expand to the atmospheric pressure while producing power. A small part of this power extracted by the turbine is used to drive the compressor. Then the exhaust gases (point 4) from the turbine are ejected in the atmosphere (not recycled), which causes the cycle to be classified as an open cycle [11].

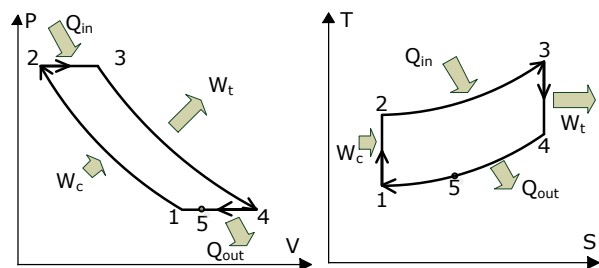


Fig. 3. The P-V and T-S diagrams for the gas-turbine engine, where 1-2 – isentropic compression (in a compressor), 2-3 – constant-pressure heat addition, 3-4 – isentropic expansion (in a turbine), 4-1 – constant-pressure heat rejection

In typical gas-turbine engines, the temperature of the exhaust gas leaving the turbine is often considerably higher, usually above 500°C [3]. This high-temperature exhaust gases can be used as the energy source for the bottoming cycles such as central heating and cooling. In this cycle, energy is recovered from the exhaust gases by transferring it in a heat waste recovery system (point 5). Energy utilization of waste heat from the gas-turbine cycle at high temperatures is discussed in the next sections.

Heat transfers to the working fluid (fuel amount) are:

$$Q_{in} = F_{CCHP} = mc_p (T_3 - T_2) \quad (8)$$

where m – the mass flow of air (gas), c_p – specific heat under constant pressure (which is a constant), T_3 – the gas temperature at the turbine inlet, T_2 – the gas temperature at the exits of the compressor.

Output power:

$$W = W_{tur} - W_{com} = mc_p [(T_3 - T_4) - (T_2 - T_1)] \quad (9)$$

where W_{tur} – the work output of the turbine, W_{com} – the work input to the compressor, T_4 – the gas temperature at the exits of the turbine, T_1 – the gas temperature at the compressor inlet.

The heat absorbed by reclamation system in waste heat recovery system is:

$$Q_{out} = mc_p (T_4 - T_5) \quad (10)$$

where T_5 – the exhaust gas temperature.

The cooling power necessary for absorption cooling system is:

$$R = \kappa \cdot COP \cdot Q_{out} = \kappa \cdot COP \cdot mc_p (T_4 - T_5) \quad (11)$$

where κ – the rate of heat used for cooling.

The heating capacity H of the CCHP system is:

$$H = (1 - \kappa) Q_{out} = (1 - \kappa) \cdot mc_p (T_4 - T_5) \quad (12)$$

After substitution of (5), (6), (8) and (9) into (5), we can obtain:

$$TPES = 1 - \frac{T_3 - T_2}{\frac{(T_3 - T_4) - (T_2 - T_1)}{\eta_W^{sp}} + \frac{(1 - \kappa) \cdot (T_4 - T_5)}{\eta_Q^{sp}} + \frac{\kappa \cdot COP \cdot (T_4 - T_5)}{COP^{sp} \eta_W^{sp}}} \quad (13)$$

As a consequence, the economy of primary energy in the trigeneration system can be written depending on the Power to Heat Ratio:

$$TPES = 1 - \left[\frac{T_4 - T_5}{T_3 - T_2} \cdot \left[\frac{PHR}{\eta_W^{sp}} + \frac{1}{\eta_Q^{sp}} - \left(\frac{1}{\eta_Q^{sp}} \cdot \frac{COP}{COP^{sp} \eta_W^{sp}} \right) \cdot \kappa \right] \right]^{-1} \quad (14)$$

The calculations of the trigeneration system performance were carried out for the following parameters:

- The reference efficiency for the conventional separate generation of electricity $\eta_{wsp} = 40\%$; the reference efficiency for the conventional separate generation of thermal energy $\eta_{Qsp} = 90\%$; the coefficient of performance of the compression chiller $COP^{sp} = 5$.
- The operating temperatures measured in the real CHP plant: the gas temperature at the compressor inlet $T_1 = 20^\circ\text{C}$; the gas temperature at the turbine inlet $T_3 = 1050^\circ\text{C}$; the gas temperature at the exits of the turbine $T_4 = 540^\circ\text{C}$; the exhaust gas temperature leaving the power plant $T_5 = 90^\circ\text{C}$.

On the basis of (13), energy saving performance was defined depending on the changing rate of heat used for cooling (κ) and different equipment performance characteristics.

In this light, Figure 4 shows a plot of the trigeneration primary energy savings depending on the changing rate of heat used for cooling. As a general result, the $TPES$ indicator decreases when k increases. The analysis shows that the maximum value of the primary energy savings are obtained when the participation of heat used for production of cold is zero ($\kappa=0$). Hence, the trigeneration

system functions in cogeneration regime. If a part of the heat from cogeneration is used for the production of cold, the energy saving characteristics of trigeneration decreases even to zero, where all the heat generated in cogeneration is used for cooling ($\kappa=1$). In the case of using the refrigeration equipment with high performance, the $TPES$ indicator varies to a small extent. This mean that the quantitative participation of heat used for cooling production has little effect on the energy efficiency of the system.

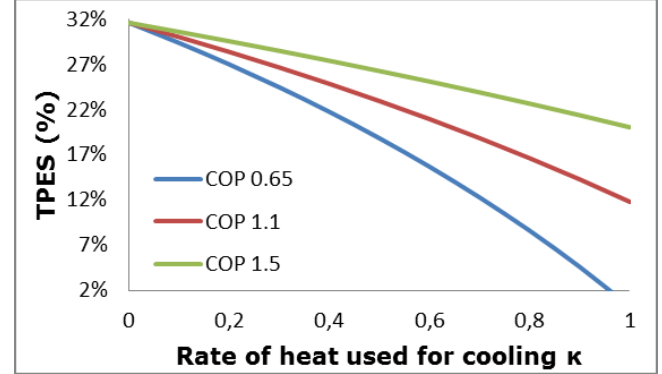


Fig. 4. Trigeneration primary energy saving depending on κ and COP

Admittedly, reuse of the waste heat comprised in the hot exhaust gas flowing from the gas turbine to produce steam or warm the heating water increases the overall efficiency of the energy system, but does not actually increase the efficiency of the Brayton cycle. Therefore, every effort is made to improve the efficiency of the cycle in which gas-turbine plants operate. The primary method to improve the cycle efficiency of a gas-turbine is to increase the turbine inlet temperature T_3 [3], which is mainly related to with the increase of the maximum circuit temperature and may be limited due to the heat-resistance of the engineering elements. Currently, the most commonly used systems do not exceed the maximum temperature of 1500°C.

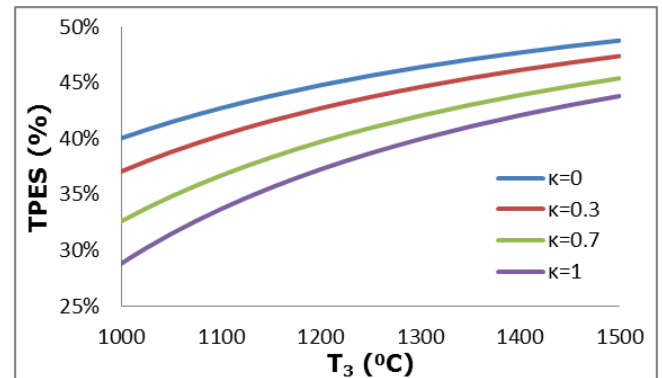
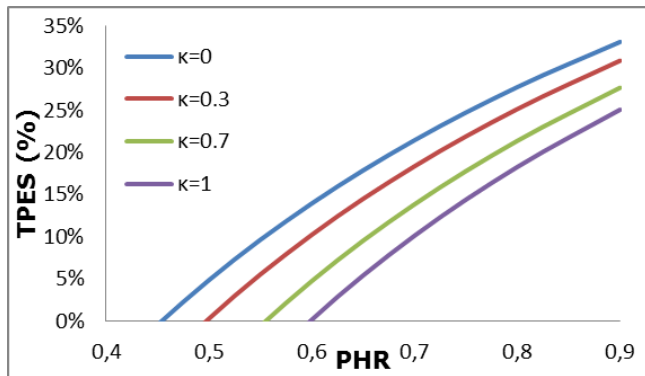


Fig. 5. Trigeneration primary energy saving depending on the turbine inlet temperature T_3

Figure 5 shows the effects of an increase of the gas temperature at the turbine inlet on the energy saving performance of the trigeneration system for different rates of heat used for cooling. In particular, the amount of primary energy savings depend upon the operational temperatures and increase with increasing the gas temperature at the turbine inlet.

As a consequence from Figure 4, it is more profitable to use the heat from cogeneration for heating purposes rather than for feeding the absorption chiller. Nonetheless, CCHP can produce electricity, heat and cooling at the same time, and it reaches a high energy utilisation efficiency. From the energy saving standpoint, it is necessary to study the influence of the Power to Heat Ratio on the energy saving efficiency.



Rys. 6. Trigeneration primary energy saving depending on Power to Heat Ratio

According to Figure 6 above, the PHR indicator has an impact on energy saving efficiency. This means that, if the electrical efficiency is low, trigeneration may not show the energy savings in comparison to separate production. Hence, the trigeneration systems can be advantageous if the Heat Power Ratio is greater than 0.6. As a consequence, the electrical efficiency has to be more than 40%. In addition, the present analysis may be helpful to optimise trigeneration processes.

4. Conclusions

Based on the above analysis of the trigeneration system the following conclusions can be drawn:

- 1) The rate of the energy saving efficiency is raised with the increases of electrical efficiency and can achieve more than 40%.
- 2) The maximum value of the primary energy savings obtained is when $\kappa = 0$, when the system works as cogeneration.
- 3) The use of refrigeration equipment with a higher Performance Coefficient helps to maintain the value of the *TPES* indicator above zero, which proves a high efficiency of trigeneration.
- 4) Growth of the gas temperature at the turbine inlet increases the energy efficiency of the gas turbine and allows to reduce the primary energy consumption.
- 5) A properly selected *PHR* indicator, depending on demand of electricity, heat and cooling can be a helpful tool for the process of optimising the trigeneration and allows to achieve the best trigeneration system efficiency for selected working conditions.

Trigeneration can be attractive for consumers with simultaneous demand for all three products such as electricity, heat and cooling. Therefore, typical trigeneration users can be hospitals, office building, hotels, food industry and other activities related to refrigeration [1, 2, 7].

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